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Title: Imaging Brunelleschi's cupola wall using Muon scattering radiography

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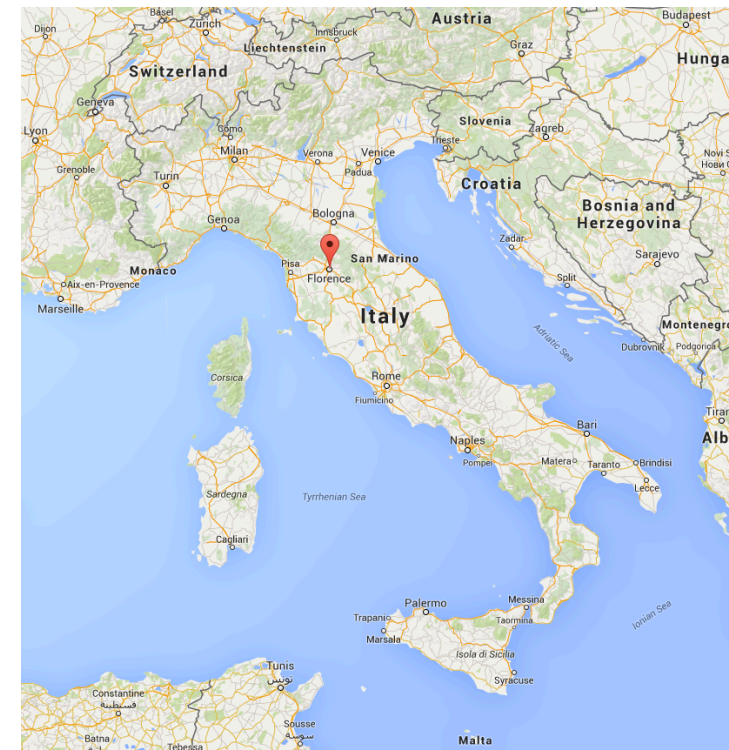
The background of the slide is a photograph of the Florence Cathedral (Duomo) and its surrounding cityscape. The cathedral's large, red-tiled dome is the central focus, with its intricate facade and the adjacent Giotto's Campanile visible. The city of Florence, with its characteristic terracotta-roofed buildings, is seen in the foreground and middle ground, set against a backdrop of rolling hills under a hazy sky.

IMAGING BRUNELLESCHI'S CUPOLA WALL USING MUON SCATTERING RADIOGRAPHY

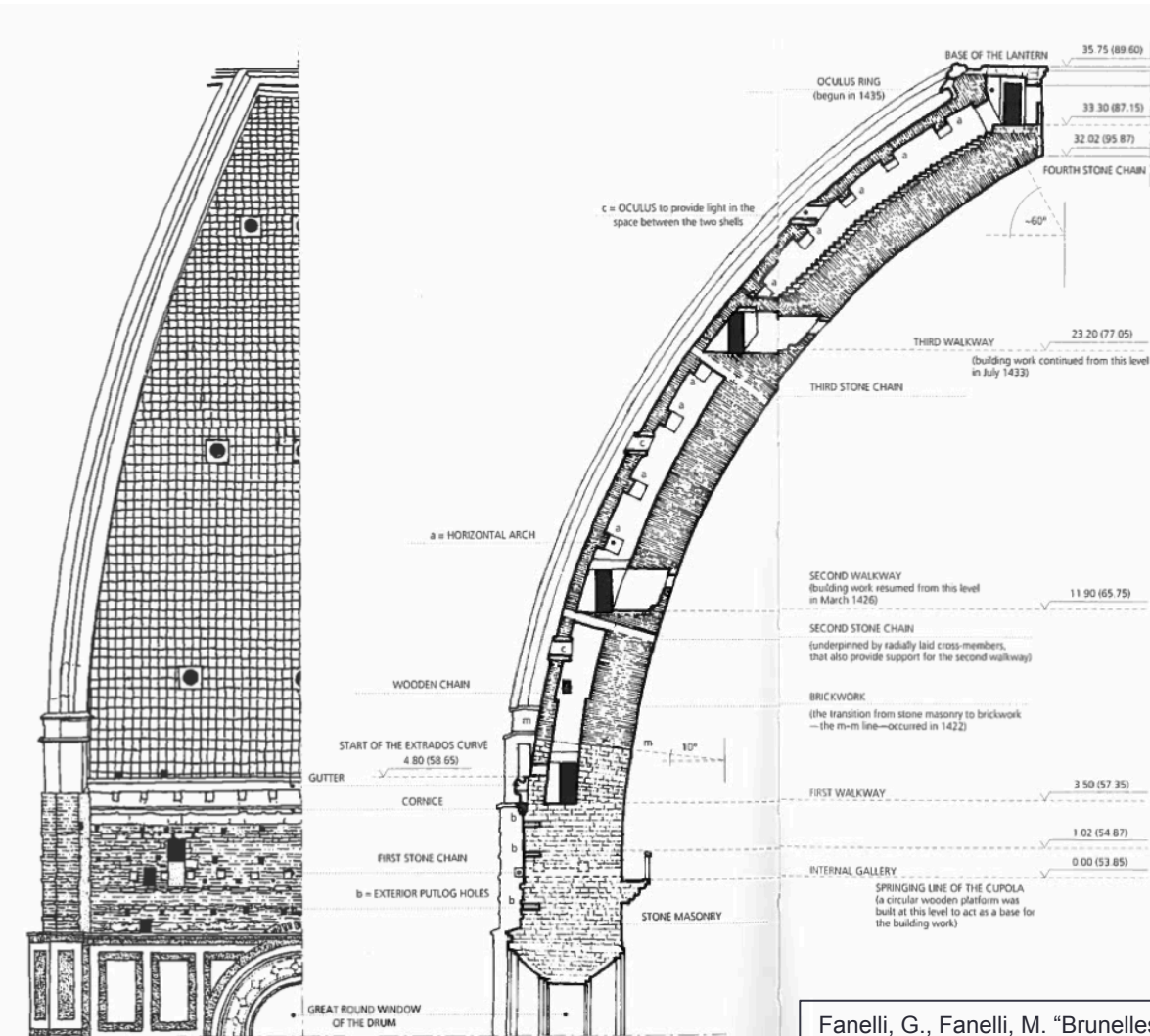
Elena Guardincerri for the Threat Reduction team

Brunelleschi's Cupola

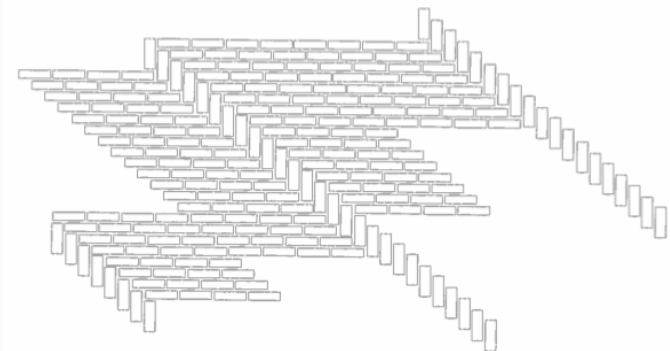
- Dome of Santa Maria del Fiore, the Cathedral of Florence, Italy.
- The church is today one of the UNESCO World Heritage sites and among the highest profile buildings in existence.
- Its Dome was built between 1420 and 1436 under the direction of Filippo Brunelleschi.
- Octagonal base: the diameter of the circle circumscribed to the octagon is 44.308 m.



Brunelleschi's Cupola

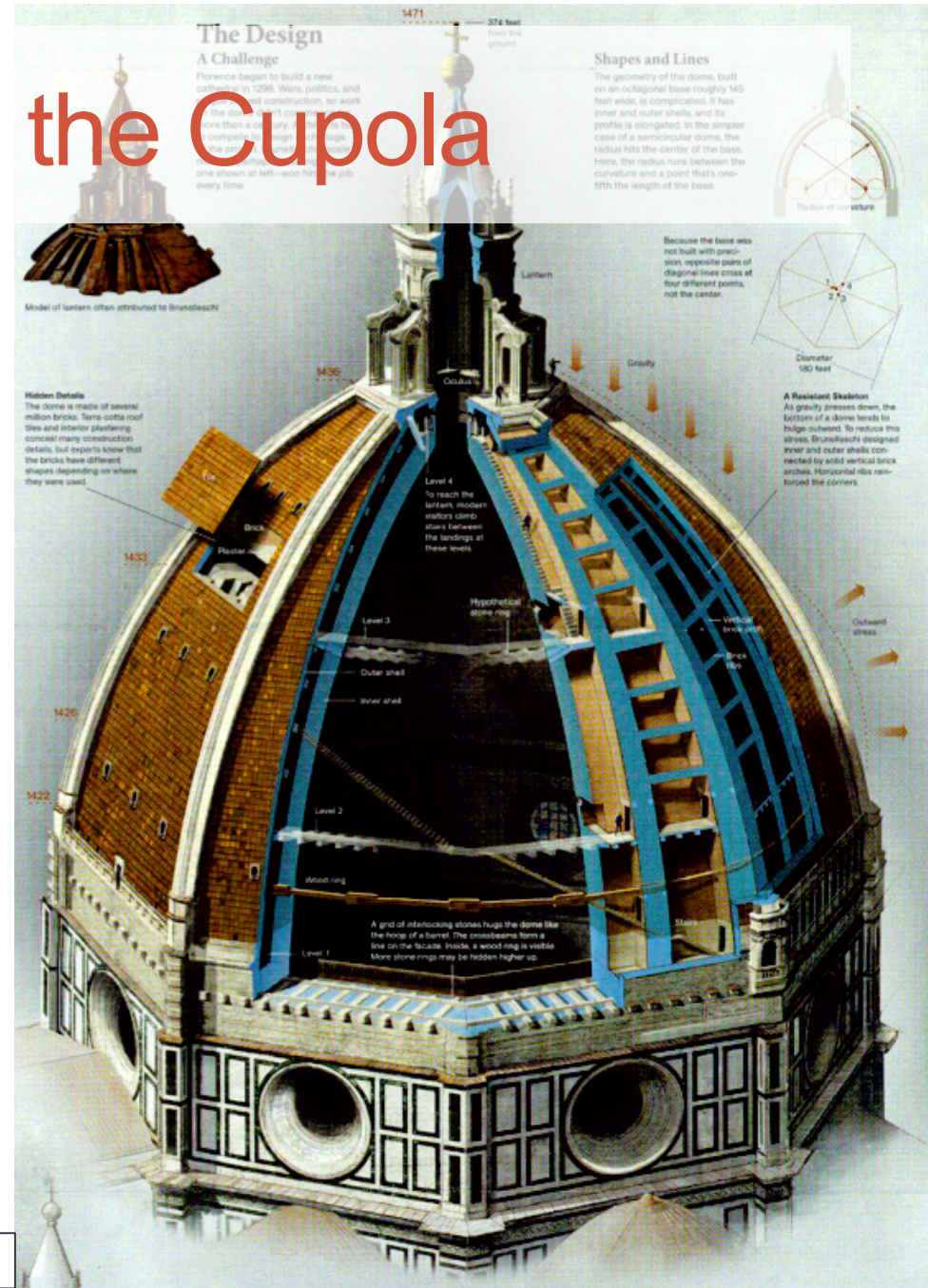


- Made of two shells, the inner one 2.25m thick at the base, the outer one 0.8m thick.
- Built out of sandstone blocks up to ~ 7m above the springing, brickwork above.
 - Bricks arranged in a herringbone pattern: "spinapesce".
- Was built without centering (no temporary support structure)

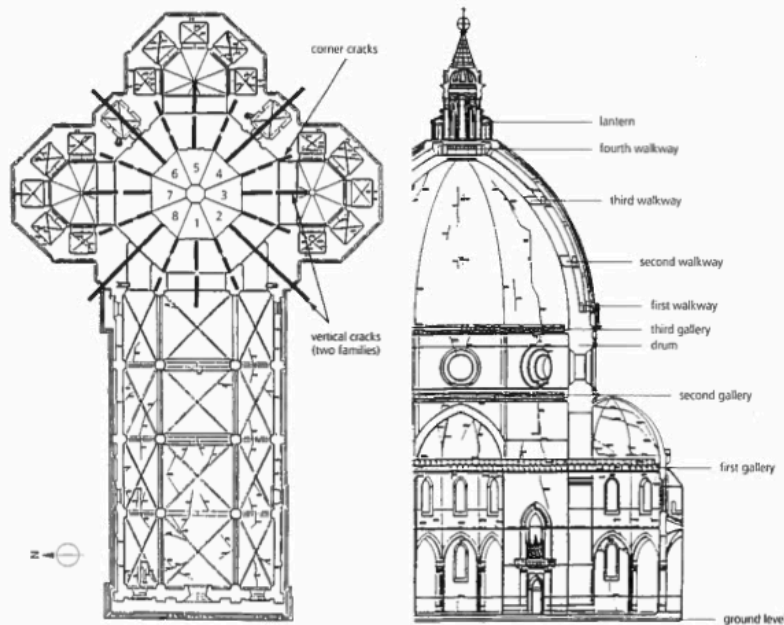


Reinforcements in the Cupola

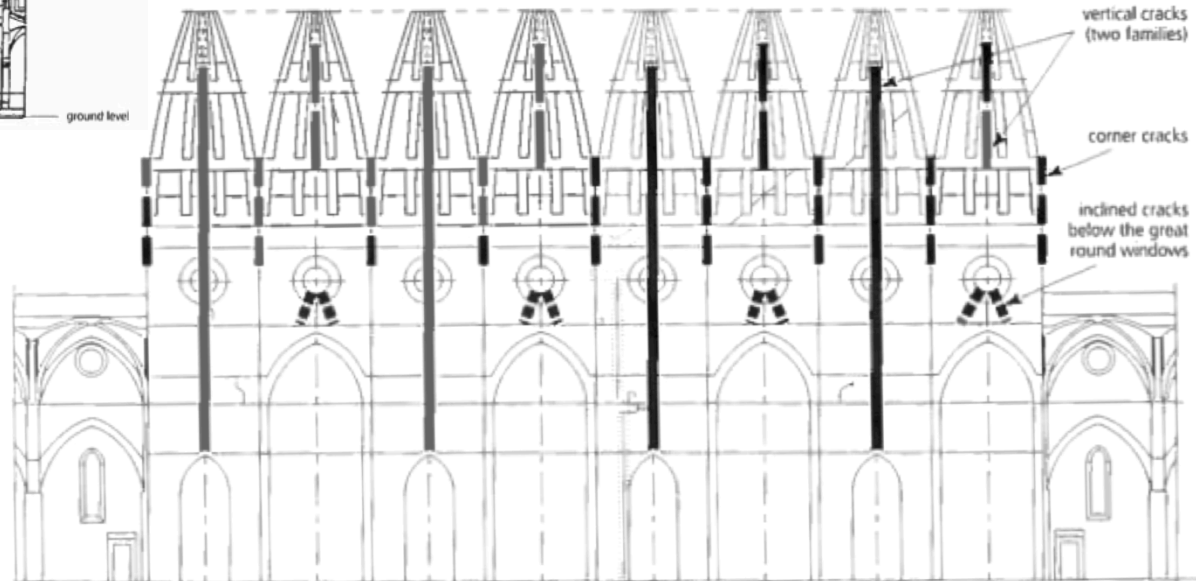
- Three pairs of *macigno* chains are believed to reinforce the Cupola.
 - Only the existence of the lowest pair have been proven.
- A wooden chain was also installed 7.75 m above the springing of the Cupola.
- Some scholars maintain that there are also iron chains inside the masonry.
 - Investigations with metal detectors have failed to yield conclusive evidence.
 - Thousands of Florentine pounds of iron (1 pound = 0.34 kg) were purchased during the construction of the dome.



The cracks



- The dome has been affected by cracks for centuries. They likely appeared shortly after the completion of the Cupola, they were first mentioned in 1639.
- Their width increases by 7.5 mm/century.
- The largest are up to 6-8 cm wide.



Muon tomography applied to the Cupola

- A detailed knowledge of the structure of the Cupola would benefit the finite element calculation models that are used to evaluate its behavior under static and dynamic (earthquakes) conditions.
 - Brunelleschi purposely didn't leave drawings
- Multiple scattering muon radiography could be used to image the inside of the dome's walls.
 - Iron elements could be seen
 - The cracks profile inside the wall could be determined, and this would shed light on how the wall itself was built.
 - Brick pattern
 - ... or just the two visible brick walls filled with gravel and mortar?
 - How deeply were the cracks filled during the past centuries?



Partially filled segment of a crack

Demonstration measurement at LANL

- During the summer of 2015 we performed a demonstration measurement at LANL, funded by the LDRD program.
- We built a concrete wall having the same thickness, in radiation lengths, as the inner (and thicker) wall of the Dome and we placed three iron bars inside it.
- The cross sections of the bars are square/rectangular.
- Their dimensions were:
 - 4.76 cm x 5 cm
 - 2 cm x 3 cm (the bars in the Cupola wall are believed to be this size)
 - 10 cm x 10 cm.



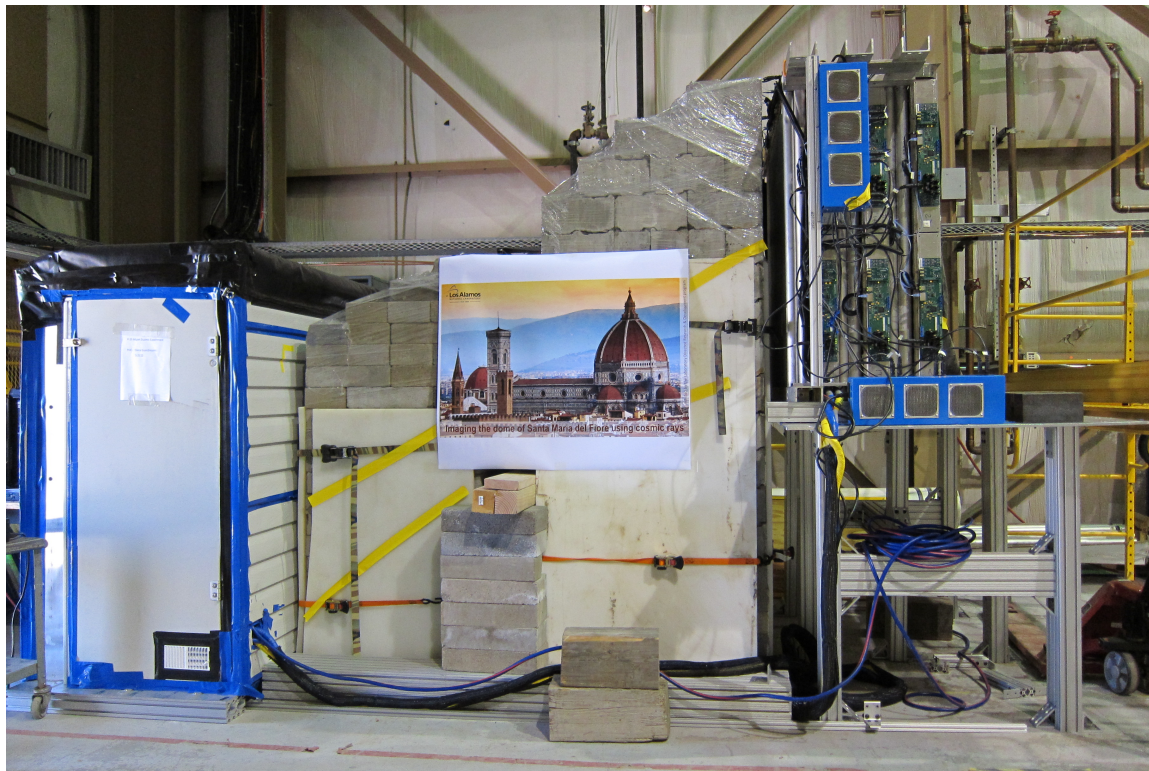
The mock-up wall after its completion, with the students who built it.



The iron bars inside the wall

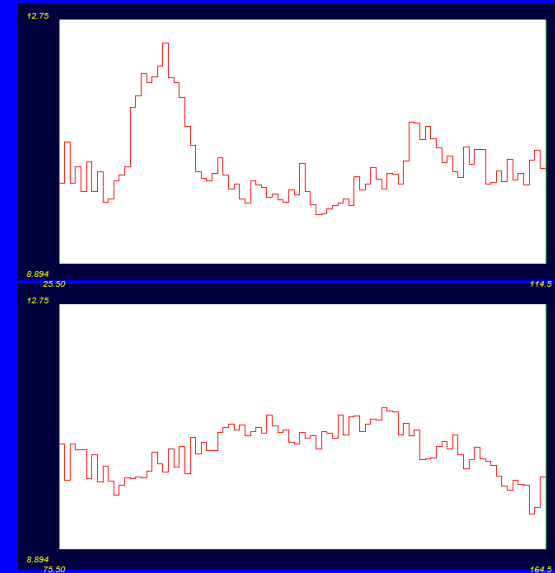
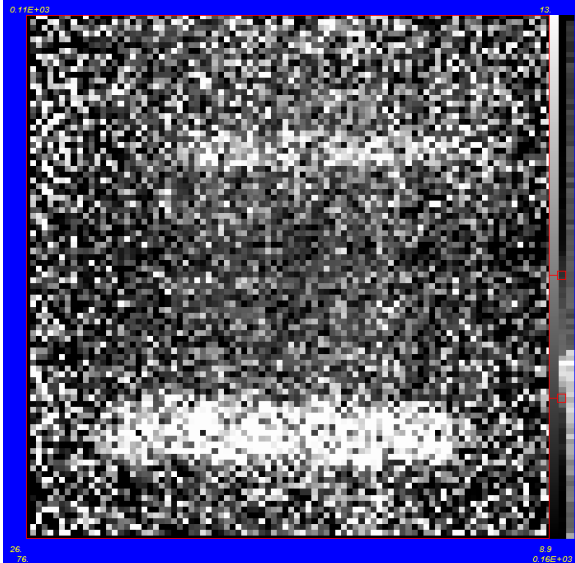
Demonstration measurement at LANL

- We deployed our two muon tracker modules on two opposite sides of the wall and took data for 35 days.



Demonstration measurement at LANL

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cnts/ych: 999.4  
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xbar: 120.0 xrms: 25.66 ybar: 69.73 yrms: 26.08
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- The picture shows our results after 35 days of data taking. All the bars are visible. The thinnest bar was already visible after 17 days.

Approval from the Opera del Duomo

- I presented these results in Florence on 8/31/15 to a team composed of professors and researchers from the universities of Parma and Florence, and to the president of the Opera del Duomo, the corporation that manages the church since its construction in the 13th century.
- Our results were very positively received and we had the approval to proceed from the Opera del Duomo.
- I also visited the Cupola with some experts to determine where the detectors could be deployed and what specifications they should meet.
- The US Consul General in Florence, Ms. Abigail Rupp, invited me on 9/1/15 to the consulate where I described her our project
 - She was extremely interested and appreciative and offered her help.

Detectors requirement and plan

- We agreed to aim for a measurement in the rib vault number 6 of the dome (number 1 is the one aligned with the central nave of the church, then they are numbered clock wise when looking up from the floor), above the higher walkway and below the lowest oculus.
- One detector would be inside the dome, the other between the two shells.
- The rib vault number 6 is the one with the widest crack, and the region selected is the one where most likely there could be iron bars/clamps.
- Furthermore, in this area, there is the transition between stonework and brickwork, which could be seen, and the famous macigno chain.
- This area is also the one where the crack is wider (6-8 cm), and its shape through the wall could be determined.



We will focus on this region

Detectors requirements and plan

- Our detectors should be as light as possible, and thinner than they currently are
- Two 200 lb modules, 30 cm thick are acceptable.
 - This could be done using 1in diameter carbon fiber tubes.
 - The detectors will have to be partially assembled in situ due to the narrow stairs with sharp curves that lead to the location where they should be deployed.
 - Deploying and moving the detector inside the dome itself will be particularly challenging, since it will likely be suspended due to the shape of the Cupola.
 - Work will have to be done on this.
- Toshiba is interested in in building the detectors.
 - They have some R&D funds they are willing to use.

Conclusions

- The measurement performed at LANL proves that muon scattering radiography is a viable technique for imaging the inside of the Cupola wall.
- The measurement on the dome will provide information that may help to evaluate its stability and thus preserve this important cultural site.
- LANL, Toshiba, the Parma and Florence universities and the Opera del Duomo are willing to collaborate on such effort
- The project will have a tremendous visibility worldwide.



Views of Florence from the top of Brunelleschi's Dome